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Petrophysics and mineral exploration: a workflow for data analysis and a new interpretation framework

Michael Dentith[1]*, Randolph J. Enkin[2], William Morris[3], Cameron Adams[1] and Barry Bourne[4]

[1] *Centre for Exploration Targeting, School of Earth Sciences, The University of Western Australia, Crawley, WA 6009, Australia,* [2] *Geological Survey of Canada, Sidney, BC V8L 4B2, Canada,* [3] *School of Geography and Earth Sciences, McMaster University, Hamilton, ON L8S 4L8, Canada, and* [4] *Terra Resources, 8 Kearns Crescent, Ardross, WA 6153, Australia*

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ABSTRACT

As mineral exploration seeks deeper targets, there will be a greater reliance on geophysical data and a better understanding of the geological meaning of the responses will be required, and this must be achieved with less geological control from drilling. Also, exploring based on the mineral system concept requires particular understanding of geophysical responses associated with altered rocks. Where petrophysical datasets of adequate sample size and measurement quality are available, physical properties show complex variations, reflecting the combined effects of various geological processes. Large datasets, analysed as populations, are required to understand the variations. We recommend the display of petrophysical data as frequency histograms because the nature of the data distribution is easily seen with this form of display. A petrophysical dataset commonly contains a combination of overlapping sub-populations, influenced by different geological factors. To understand the geological controls on physical properties in hard rock environments, it is necessary to analyse the petrophysical data not only in terms of the properties of different rock types. It is also necessary to consider the effects of processes such as alteration, weathering, metamorphism and strain, and variables such as porosity and stratigraphy. To address this complexity requires that much more supporting geological information be acquired than in current practice. The widespread availability of field portable instruments means quantitative geochemical and mineralogical data can now be readily acquired, making it unnecessary to rely primarily on categorical rock classification schemes. The petrophysical data can be combined with geochemical, petrological and mineralogical data to derive explanations for observed physical property variations based not only on rigorous rock classification methods, but also in combination with quantitative estimates of alteration and weathering. To understand how geological processes will affect different physical properties, it is useful to define three end-member forms of behaviour. Bulk behaviour depends on the physical properties of the dominant mineral components. Density and, to a lesser extent, seismic velocity show such behaviour. Grain and texture behaviour occur when minor components of the rock are the dominate controls on its physical properties. Grain size and shape control grain properties, and for texture properties the relative positions of these

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*E-mail: michael.dentith@uwa.edu.au

grains are also important. Magnetic and electrical properties behave in this fashion. Thinking in terms of how geological processes change the key characteristics of the major and minor mineralogical components allows the resulting changes in physical properties to be understood and anticipated.

Key words: Data processing, Interpretation, Petrophysics.

INTRODUCTION

The most common objective when working with petrophysical data during exploration for minerals is to define physical property contrasts associated with the local geology as a means for understanding likely sources of observed variations in geophysical interpretation products. This may be with the intention of determining what is being 'mapped' during a qualitative analysis of geophysical imagery and/or to quantify physical property contrasts prior to modelling observed responses.

Table 1 compares petrophysical practice in the mining and petroleum sectors and is instructive in that it highlights how much more advanced petrophysical practice is in the petroleum sector compared to the mining sector. In the petroleum industry, large data volumes and multiple data types are routinely analysed in a strong conceptual and empirical context. Petrophysical data is viewed as an essential source of information and its analysis is an integral part of the exploration and production workflow. This work, which is carried out by a 'petrophysicist', is seen as a distinct discipline; it has its own professional society. In contrast, in the mining industry, petrophysics is a relatively minor component of work usually undertaken by geophysicists. Some companies routinely make petrophysical measurements on core, most commonly magnetic susceptibility. In other companies, petrophysical data are only acquired when there is a need to understand some particular set of geophysical observations. In many cases, little use is made of the results and analysis is usually in terms of lithologically related variations only.

In this paper, we discuss how petrophysical data can be better understood in a geological context and highlight some of the problems with current practice, for example the need for larger datasets to ensure representative data are collected. We suggest some improved methods of data presentation and analysis in the context of geophysical exploration. We argue that the availability of portable devices that provide quantitative geochemical and mineralogical data means the opportunity exists to make significant progress in understanding rock properties in mineralized environments and for petrophysics to become much more important in mineral exploration. We concentrate on density and magnetic susceptibility data, as these are by far the most common types of petrophysical data used by the mining industry.

FUTURE OF PETROPHYSICS IN MINERAL EXPLORATION

Because mineral deposits with a surface expression have largely been discovered, mineral exploration is increasingly seeking targets that are deeper and under a near-surface cover sequence. This means there will be greater reliance on geophysics and hence a need to obtain the most geologically reliable interpretations from geophysical datasets. Physical property data become essential when these geophysical datasets are interpreted with fewer geological constraints than for shallower targets because of the high cost of deep drilling. When a cover sequence is present, one needs information regarding the petrophysical properties of the cover rocks to effectively minimize their impact on the observed geophysical responses thereby enhancing any signal associated with targets located beneath the cover rocks. Examples of this problem include the impact of near-surface conductors on electrical and electromagnetic responses in Australia, or magnetic overburden on magnetic anomalies in Canada.

A review of published literature and current industry practice suggests less progress in petrophysics compared to geophysical data acquisition, processing and modelling. One reason for this may be the discipline-spanning nature of petrophysics. To generalize, making a petrophysical measurement is a problem in physics which has been largely solved and is easily achieved with readily available instrumentation, albeit with some outstanding questions regarding the way the data are collected (see below). In contrast, understanding the geological significance of the measurement is a problem in chemistry and mineralogy, an area in which many geophysicists have limited understanding.

Table 1 A comparative summary of how petrophysical data are used in the petroleum and mining industries

Petroleum Petrophysics	Mining Petrophysics
Primary interest is the pore space and its contents	Primary interest is in the matrix of what are mostly low porosity rocks
Rocks are typically layered, facilitating seismic surveys.	Rocks typically have complex geometry, limiting use of seismic methods, but displaying prominent lateral contrasts for gravity, magnetic and electric surveys.
Heavily reliance on well logging, resulting in large datasets comprising *in situ* measurements	Downhole logging still comparatively rare and data often comprise a small number of measurements made on core or outcrop
A suite of downhole logs measuring a diverse range of properties is routinely acquired: sonic(velocity), density, neutron, natural gamma, various electrical measurements and temperature	In the relatively rare instance that downhole logs are acquired, these tend to be few in type. The most common log type is natural gamma, probably followed by density and susceptibility logging
Televiewers routinely used	Televiewers only used in a few specialist applications usually associated with geotechnical work associated with mining rather than exploration
Analysis relies heavily on multi-parameter datasets interpreted in combination	Combined analysis of multiple types of measurement much less common and when undertaken a limited number of data types are used
Routine use of quantitative methods of data analysis, either empirical or based on theoretical studies	Analysis is rudimentary, usually comprising derivation of a few simple statistical parameters and, if different kinds of data are available, simple cross plots
Instrument calibration facilities and industry-wide standards for data acquisition universally adopted	No industry-wide instrumentation standards or data acquisition and analysis practices

The petrophysical measurement is of course numerical, but the geological information available is usually categorical. Not only is the geological data categorical, but many geological terms, for example rock type, are subjective, context-dependent and necessarily unspecific. For example, the mineralogical classification of a rock as a particular kind of granitoid allows for ranges in the abundance of the key minerals. Also, there is no universally adopted rock classification scheme and even when individual companies adopt a specific scheme, experience shows that which geologist has logged a drill core is frequently a significant control on how the rocks are described. These factors hinder the integration of geological and petrophysical information. Importantly, this situation can be improved, at least with respect to measurements on samples, with the widespread availability of portable geochemical and mineralogical analysis instrumentation, for example portable X-ray fluorescence and hyperspectral spectrometers. Semi-portable systems that simultaneously acquire geological and petrophysical data from core are also now available (Ross, Bourke and Fresia 2013). Put simply, geological information is now easily available in numerical form and can be obtained using portable instruments, which means petrophysical measurements can now be analysed within a much more rigorous geological context.

Historically, in most mining industry, petrophysical data have been analysed primarily in terms of local lithological context, that is rock type. This is useful in many situations, especially when using geophysics for geological mapping. Although assigning a rock name to a specific lithology unit may convey implicit information about, say, its metamorphic state, looking at the data in contexts other than rock type provides much useful additional information. For example, the wide spread adoption of the mineral systems concept (Wyborn, Heinrich and Jaques 1994) suggests an important alternative context. The mineral systems concept suggests formulating exploration strategy within the context of fluid and/or metal source zones, fluid flow paths (including those post deposition of metals) and the postulated palaeo-reservoir zones along the pathway where fluids were trapped prior to release in transient flow events (McCuaig and Hronsky 2014). Geophysical responses from the various mineral system components are likely to be large due to changes in rock properties (mineralogy, grain size and porosity) caused by alteration associated with fluid–rock interactions. Although there are several groups now working on remedying the situation, the petrophysical consequences of many forms of alteration (e.g. talc-carbonate and albitization) are poorly documented and much less well understood when compared to lithological controls on physical properties.

DATA ACQUISITION

It is not our intention to discuss the relative merits of different measurement practices, although we note there is no standard methodology adopted within the mining industry. Here we restrict our comments to the important question of whether enough data have been acquired so as to be representative of actual variations in physical properties.

Figure 1(a) shows the variations in magnetic properties as a function of position within a lava flow in the oceanic crust (Delius, Brewer and Harvey 2003). The variations in magnetic properties are large, with variations of orders of magnitude occurring over distances of decimetres. To state the obvious, the measured petrophysical property is critically dependent on where the measurement is made. To properly represent the actual variations in some geological unit, and to accurately calculate useful summary statistics, is clearly going to require a lot of measurements systematically distributed across the sampling zone.

When magnetic susceptibility measurements are made on core or outcrops using a portable susceptibility meter, normal practice are to collect a relatively small number, perhaps 5 from a given location on the core and perhaps 5–10 on an outcrop. Downhole logging produces relatively large volumes of data, but this method is not standard practice in most of the mining industry, an exception being the iron ore sector. Given that typical mineral industry practice is to make only a handful of measurements with portable instruments on cores and outcrops, it is very likely that not enough data are being acquired to represent the actual physical property variations, both in terms of magnitude and spatial variations. Empirical evidence based on the authors' experience suggests at least tens of measurements are required depending on the purpose of the measurements.

DATA DISPLAY

It is common to summarize sets of petrophysical data, often presented as a numerical table, using some kind of average, with or without some statistical measures of spread/range. Better than tabular presentations are graphical presentations such as range charts and bar and whisker plots (usually incorporating mean and various percentiles; Fig. 1b). Although this approach allows basic inferences to be drawn, we argue that it is not adequate to properly comprehend the significance of any internal variation within the petrophysical dataset. The variability of petrophysical properties, and the fact that often the data represent the combined effects of different geological influences, suggests it is more appropriate to analyse the data in terms of populations using frequency histograms and cumulative distribution plots (also called probability plots; Fig. 1b), rather than seeking representative individual numerical values from datasets. This approach is not new, see, for example, Lapointe, Morris and Harding (1986), Mwenifumbo *et al.* (2004), Wendt *et al.* (2013), but it has not been generally adopted.

Figure 1(b) shows frequency histograms and probability plots for the magnetism data displayed as logs in Figure 1(a). Probability plots provide evidence suggestive of multiple populations within a dataset. When the data conform to the assumed type of distribution (normal, or log-normal) appropriate to the probability plot, the data plot on a straight line. When the data comprise several populations, there are several line segments. Skewed distributions lead to distortion of the individual segments. Ideally, the presence of multiple populations in any dataset should be tested by rigorous statistical tests which are readily available in general packages such as R and Python, or targeted routines such as PeakFit. Probability plots provide a quick visual assessment if the data might comprise multiple distributions, and by implication, if there are one or more geological controls on the variations in the physical property. Frequency histograms and 'violin' plots complement the probability plots as an excellent way of qualitatively assessing the population(s) comprising the data, for example shape of distribution and number of modes. For ease of comparison, the frequency histograms are best presented in probability density form, that is the number of points in each class is normalized by the total number of data. It also important to note the number of readings contributing to the plot. The probability density histograms in Figure 1(b) clearly show that the data do not conform to an 'ideal' log-normal distribution, suggested as commonly representing populations of magnetic properties (Irving, Molyneux and Runcorn 1966; Larsson 1977; Latham *et al.* 1989). Density and velocity data often exhibit a symmetrical, mono-modal distribution but it is our experience that it is very often not the case with magnetic and electrical property data, as is shown by even a cursory glance at the data in Figure 1(b). Simple summary statistics like the arithmetic or geometric mean and standard deviation (and displays based on the same) do not capture the actual complexity. This is the primary reason we do not recommend the use of box-and-whisker plots (Fig. 1b). The 'ideal' log-normal distribution is more likely to be found in undeformed, mineralogically uniform, rocks that do not have a complex geological history. However, when the rock has undergone various post-depositional processes (weathering, alteration, metamorphism etc.), the distribution is usually much more complex.

Consider the data on intensity of remanent magnetism (Fig. 1a,c). The probability and frequency histograms

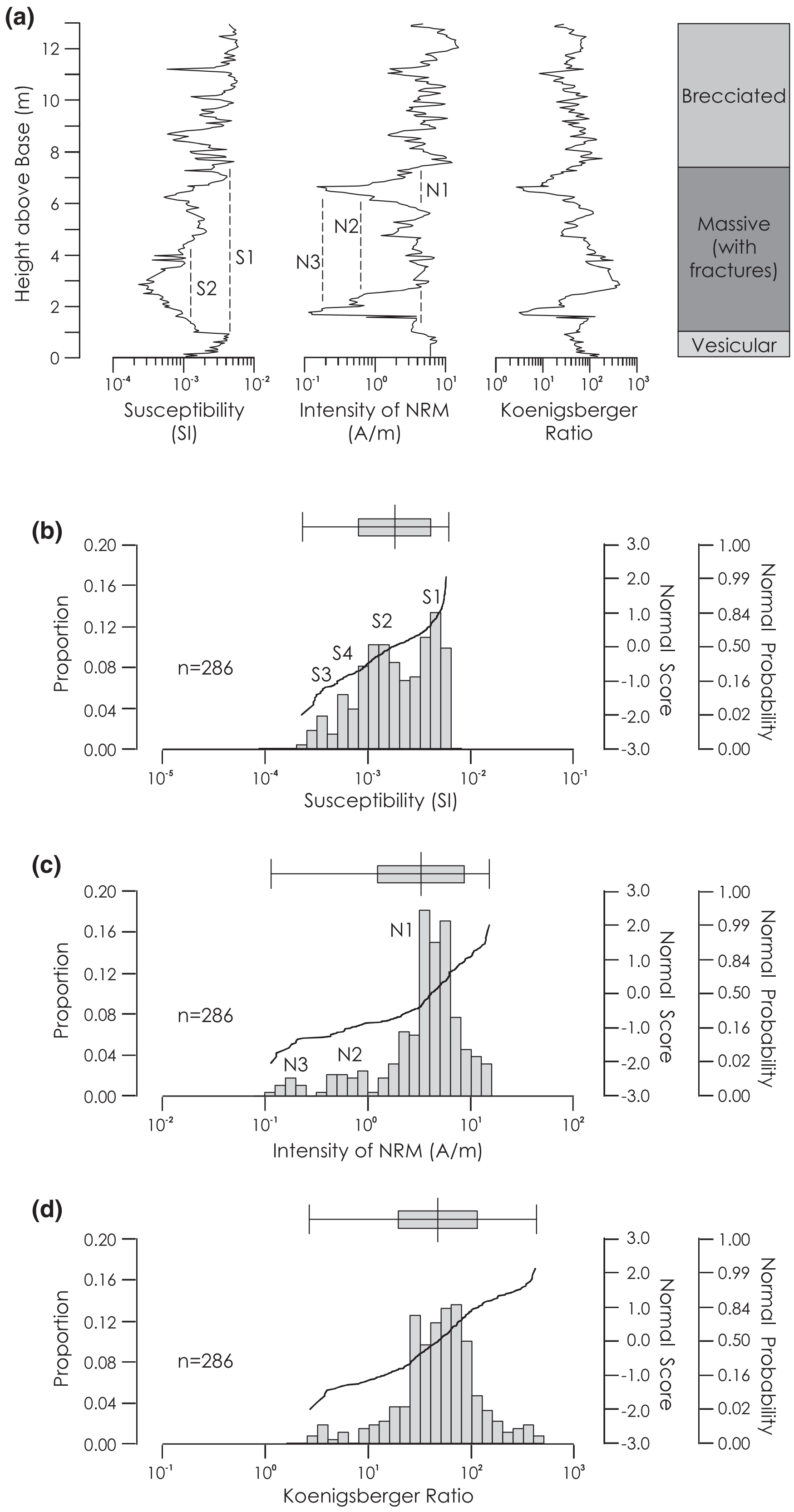


Figure 1 Magnetic property data from a lava flow in the oceanic crust. (a) Logs of magnetic properties and geological log. (b)–(d) Box-and-whisker plots, frequency histograms and probability-density curves for the data comprising part (a). N1-3 and S1-3 are modes of sub-populations within the overall population, based on data and diagrams from Delius *et al.* (2003).

suggest three sub-populations leading to three modes (N1, N2 and N3). Figure 1(a) shows two of these occur in metre-scale zones of lower magnetism within the massive part of the lava flow. Similarly, Figure 1(b) suggests there are four modes in the susceptibility distribution (S1, S2, S3 and S4), the two most important of which are again associated with the massive central section of the lava flow. Clearly, there are significant variations in the mineralogy which is responsible for both remanence and susceptibility, which may be primary or the result of later geological events, see Deluis *et al.* (2003). An important implication of the above is that understanding petrophysical datasets requires consideration of the data in terms of several different variables.

Probability density histograms allow the often complex variations within a dataset to be readily synthesized into a series of distinct sub-populations and form the basis for interpretation of the geological significance of the various population(s). For example, a bi-or multi-modal distribution associated with a single rock unit commonly arises when the lithology has been subjected to fracture-related alteration (Henkel and Guzman 1977; Lapointe *et al.* 1986). Probability density histograms also allow some level of prediction of the likely geophysical signature associated with the relevant rocks. If the distribution has a small range, then the corresponding geophysical response is likely to exhibit a relatively uniform signal. Conversely, a wide range suggests that one might expect a more variable response associated with a given rock unit. Analysing the petrophysical data in combination with analysis of the observed geophysical responses allows greater confidence to be placed in the interpretation of both.

To compare different petrophysical datasets, we create the equivalent of the stack plots used to analyse survey data in profile form (Fig. 2). We refer to these as petrophysical probability stacks. As described below, the categories (depth interval, spatial region or type of alteration) used to create the frequency histograms comprising the presentation should be more than just rock type, although this categorization is used in Figure 2. It is essential when comparing probability density displays of different datasets to create them in an exactly equivalent fashion, that is all the displays should use the same class (bin) intervals. The stacked display then allows differences between populations to be readily assessed. The magnitude of the contrast is easily seen from offsets of the peaks in the distributions being compared, and any overlap between populations is also obvious and may be evidence that the geophysical responses from the geology response for the two distributions may also be overlapping, that is indistinguishable.

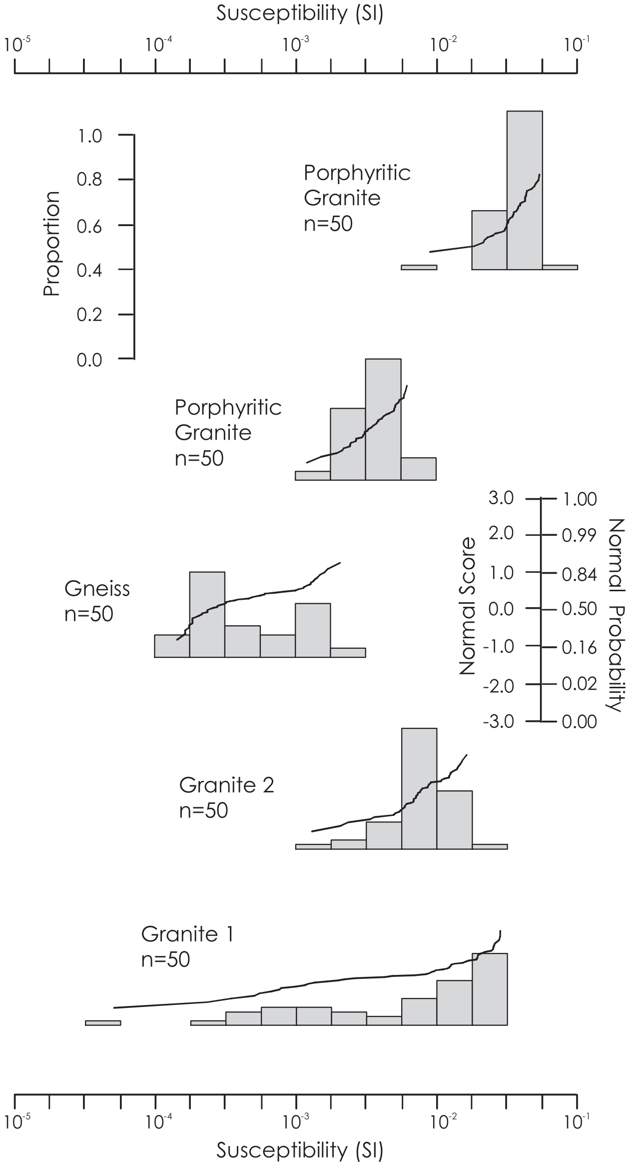


Figure 2 Petrophysical probability stack (PPS) of magnetic susceptibility data from the Dumbelyung area, Western Australia. The region comprises Archean high-grade granitoid rocks (Brakel *et al.* 1985).

PLACING PETROPHYSICAL DATA IN A GEOLOGICAL CONTEXT

Below, we describe a simple data analysis work flow which has proved useful to us. This involves classifying and then assessing the petrophysical data in the context of five different variables, these being likely geological influences on the physical properties being assessed. We use a combination of cross-plots and probability histograms to display the data.

Lithology

Most descriptions of petrophysical data classify the measurements according to the rock type on which the measurement is made. There is no doubt that lithology is an important, although not necessarily dominant, control on the observed variations. We recommend that data are categorized according to rock type as the first step in their analysis. In so doing, we note that assigning a lithological name to a rock is a subjective process, creating problems comparing observations by different individuals made at different times, and that lithological terms vary in terms of how specific they are, for example basalt versus spilite. This can create major problems associating physical property variations with specific lithotypes.

When analysing data based on lithology, it is useful to create data displays based on those used by geologists to classify rocks. This provides a more rigorous geological context and is possible provided there is equivalent geochemical and/or mineralogical data (potentially derived from measurements using portable instruments) on the same outcrops or core samples. Another advantage of these types of display is that it constitutes a form of presentation of petrophysical data that is immediately familiar to geologists. The displays also highlight the fact that geological and petrophysical similarities/differences do not necessarily correlate. This ultimately controls the correlation (or not) between a geology map and the 'pseudo-geological' map (Dentith and Mudge 2014) derived from the interpretation of geophysical data. Figure 3(b) shows density data presented using a common mineralogical and a common geochemical lithological classification scheme. The ternary diagram of modal quartz-alkali feldspar-plagioclase feldspar is commonly used to classify phaneritic igneous and metamorphic rocks. Various rock type fields are defined. In Figure 3(b), the data points are colour-coded according to density creating an easily read presentation related to the gravity response of these different rock types. Figure 3(a) is an equivalent geochemical classification diagram. The total alkalis versus silica diagram is routinely used to classify fine-grained igneous and meta-igneous rocks and again allows ready appreciation of how geophysical responses are related to lithotypes. Unfortunately, most portable XRF instruments cannot yet measure Na_2O content, and the example presented here thus depends on laboratory measurements. As discussed below, physical properties other than density are far less likely to correlate with rock type, but presentation of petrophysical data in a rigorous geological context communicates the lithological influence on physical properties in an effective way.

Secondary geological processes

Weathering, metamorphism and alteration are all secondary processes which result in some modification of the original protolith that can fundamentally affect rock physical properties.

Weathering

Weathering can significantly alter physical properties. It may increase porosity, which reduces velocity and density and increases electric conductivity. In addition, oxidation destroys magnetism, by converting magnetite and pyrrhotite to less magnetic iron minerals. Similarly, sulphides are oxidized to non-conductive and less polarizable species. On the other hand, weathering of silicate rock-forming minerals to create clay mineral species can lead to an increase in conductivity and chargeability. It is likely that any set of readings made on an outcrop is affected by weathering to some degree. The extent/depth of weathering is dependent on local current and recent past climatic systems (e.g. recent glacial activity at higher latitudes). Geophysical surveys image volumes of rock; depth of the weathering can have an impact on the resulting signal. Careful attention is needed to ensure that the petrophysical measurements are truly representative.

Consider the magnetic property data in Figure 4(a). The measurements made on both the clastic sediments and the mafic volcanics have a bi-modal distribution. This could be for one or more of the following reasons:

- The unit is inherently bi-modal, that is there are two kinds of beds with different magnetic-mineral contents and hence magnetic properties.
- These rocks have been affected by deep weathering and the population of lower values in the dataset is due to the associated reduction in magnetism. In this case, the higher modal value is more representative of the unaltered bulk of the unit.
- The outcrop has been lateritized, which involves the creation of maghaemite, and the population of higher values represents the more lateritized samples. In this case, the lower modal value is more representative of the unit as a whole.

Figure 4(b) compares magnetic properties of laterites and regolith (heavily weathered rocks) with unweathered rocks from greenstone belts in Western Australia. The laterites are highly magnetic, much more so than the bedrock lithologies. The saprolites from the regolith have much lower levels of magnetism.

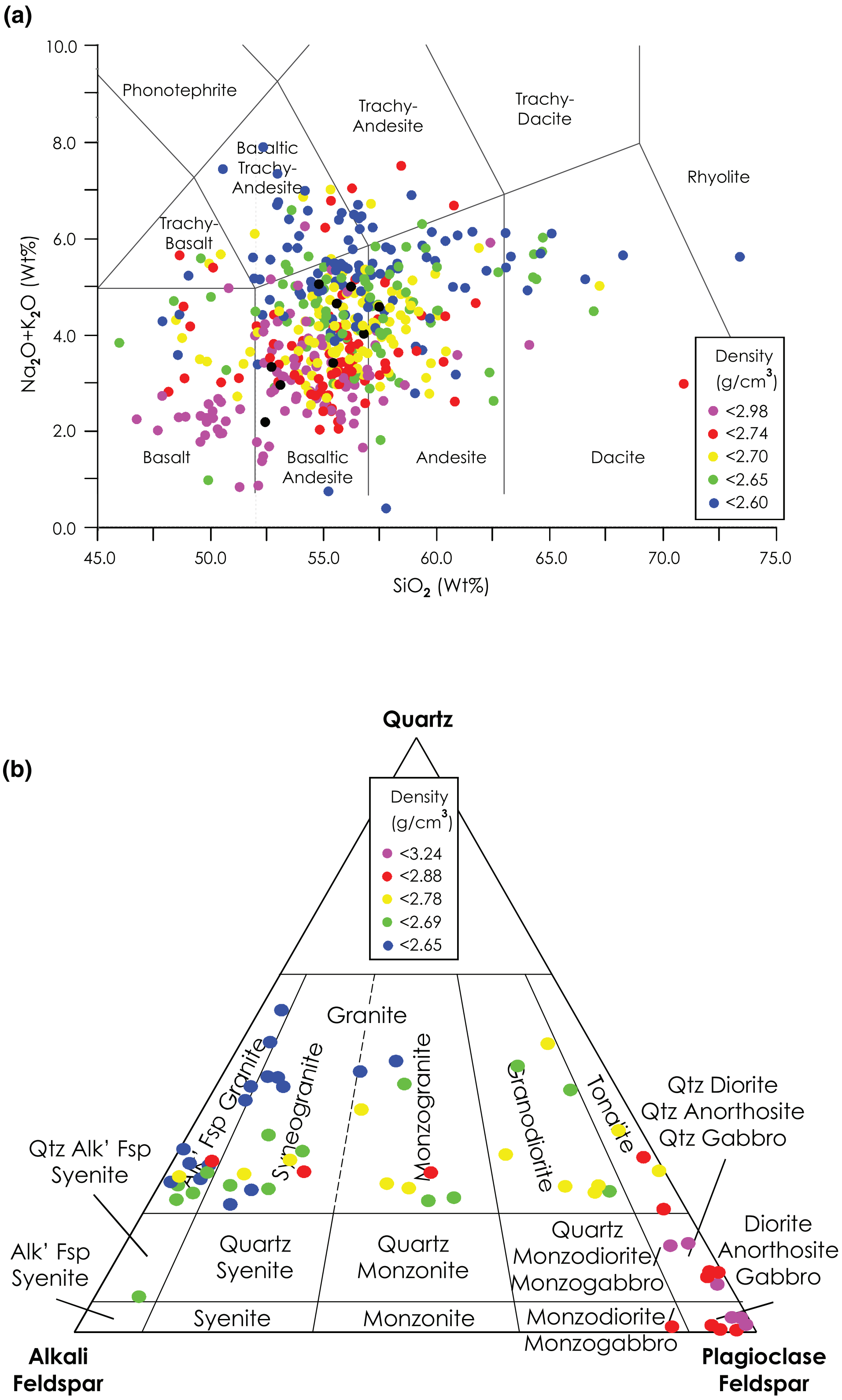


Figure 3 Density data plotted using diagrams commonly used to differentiate rock types. (a) Total alkalis--silica diagram (TAS) used for fine-grained igneous rock and (b) ternary display of leucocratic mineral content used for phaneritic granitoids.

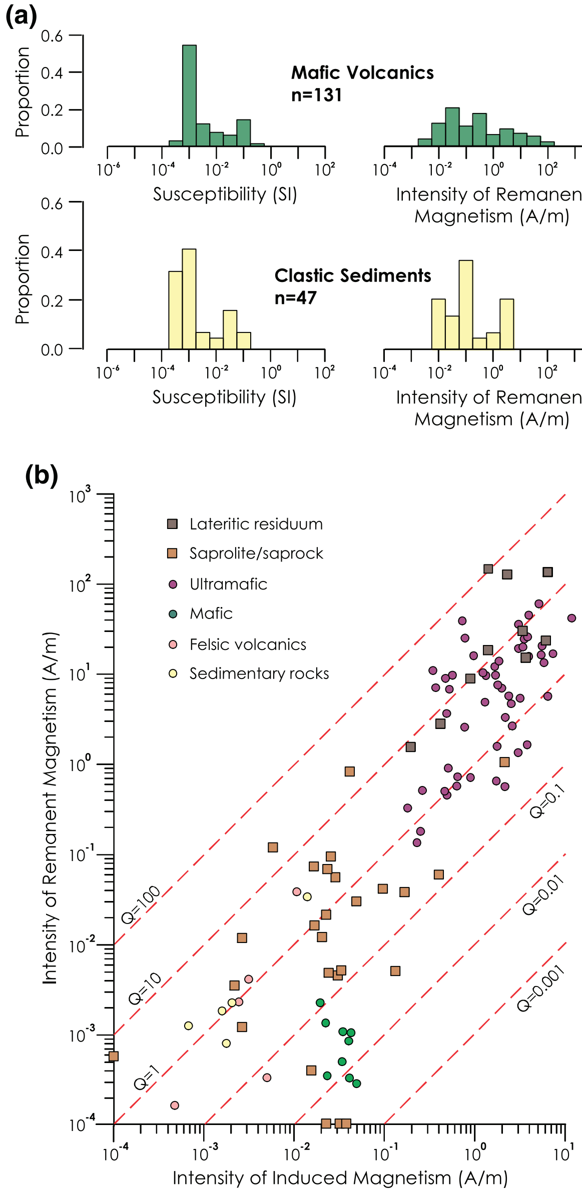


Figure 4 Frequency histogram of magnetic properties for two lithotypes from a greenstone belt in Ontario. Note the complex, multimodal, distributions; Data from Ontario Geological Survey (2001). (b) Magnetism intensity diagram for various greenstone belt lithologies from Western Australia. Note the very high values for laterites; Data from Williams (2009) and Emerson and Macnae (2001).

Ideally, the individual making the measurements notes such things as laterization, a clear illustration of the need to make careful geological observations, and certainly more than just lithology, when making measurements in the field. The points listed above also demonstrate the interpretative nature of analysis of petrophysical property datasets lacking rigorous geological control.

Engineering geologists also have qualitative ways to estimate the degree of weathering based on observed changes to a rock's appearance and its strength, for example GSL (1995). There are also numerous geochemical weathering indices, see, for example, Duzgoren-Aydin, Aydin and Malpas (2002). These indices use ratios of mobile versus immobile components based on major element analysis. Normalizing some combination of K_2O, Na_2O, CaO and MgO to Al_2O_3 is particularly common, for example the chemical index of weathering. Other indices may involve SiO_2, Fe_2O_3 and volatile content, for example Parker's index and the weathering potential index. Figure 5(a) shows data from Pola *et al.* (2012) plotted to demonstrate the correlation between the chemical weathering indices, density, seismic velocity and porosity. The physical properties in general correlate with the estimated degree of weathering, albeit some scatter and some indices are more useful as predictors of physical properties than others (at least with this dataset). Figure 5(b) shows data from the same study where the measured physical properties are plotted versus porosity, demonstrating that porosity is a key control on the physical properties. That geochemical and other weathering indices are sometimes reasonable predictors of some physical properties is largely a result of greater weathering causing greater porosity. Of course, in most circumstances, it is unlikely that field petrophysical measurements would be made on samples that are significantly weathered.

Metamorphism

Changes in metamorphic grade can fundamentally alter the mineralogy of a rock, and also change such characteristics as grain size and shape and create and destroy fabrics. Metamorphic rocks typically have their primary porosity sealed. Published studies of how metamorphism affects magnetism and density include Bourne *et al.* (1993) and for seismic properties, Hurich *et al.* (2001). From the perspective of understanding petrophysical properties, the scale of data interpretation is generally such that the regional metamorphic grade represents the 'background' properties because regional metamorphic zones commonly exist over large areas. Depending on the geological terrain however, it is possible to have sharp boundaries between regions where some physical properties exhibit a sharp transition associated with the appearance or disappearance of a particular mineral species. Olesen *et al.* (1991) describe density and susceptibility changes associated with transition between amphibolite and granulite facies in Archean rocks of northern Fennoscandia. It is well documented that thermal metamorphism associated with

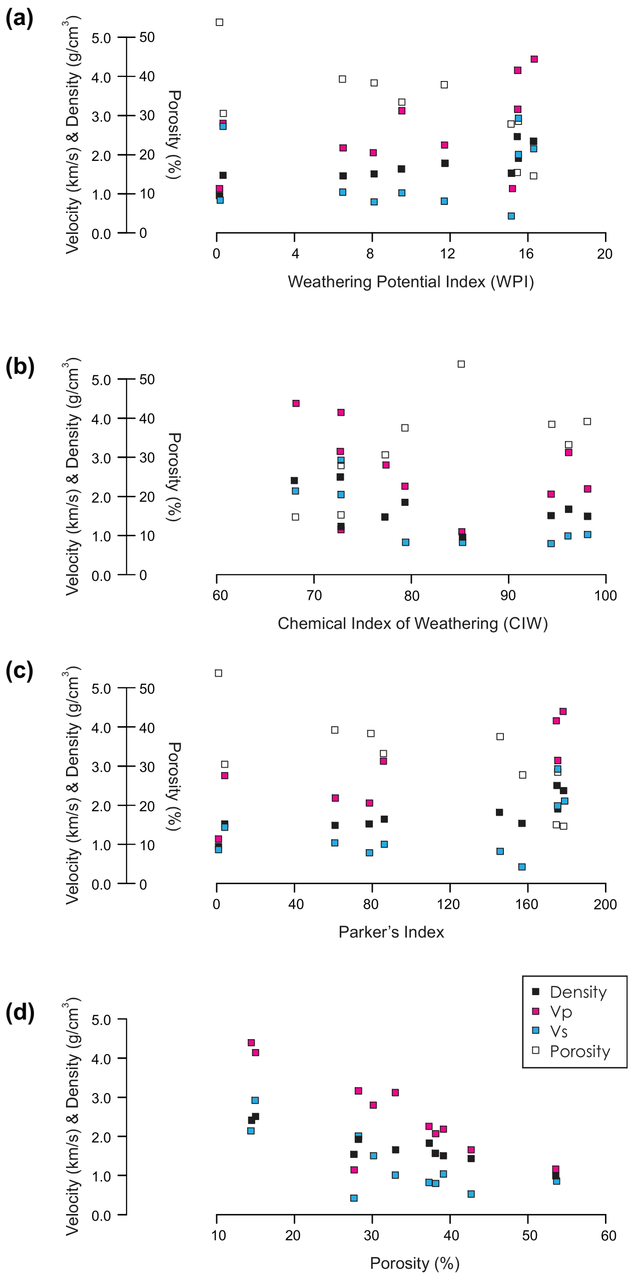


Figure 5 (a) Relationship between various chemical indices designed to quantify the degree of weathering with physical properties and porosity. Note the approximate correlation between the indices and porosity. (b) The same data as in (a) plotted to demonstrate the fundamental control of porosity on density and seismic velocity, based on data and diagrams in Pola *et al.* (2012). Weathering indices: Chemical index of weathering (CIW) = $(100 \times Al_2O_3)/(Al_2O_3 + CaO + Na_2O)$; weathering potential index (WPI) = $(100 \times (K_2O + Na_2O + CaO - H_2O^{+}))/(SiO_2 + Al_2O_3 + Fe_2O_3 + TiO_2 + CaO + MgO + Na_2O + K_2O)$; Parker's index = $100 \times ((Na/0.35) + (Mg/0.9) + (K/0.25) + (Ca/0.7))$. See Duzgoren-Aydein *et al.* (2002) for a more detailed description of the various indices.

contact aureoles can cause magnetic responses in the rocks surrounding large intrusions (Schwarz 1991; Kontny and Dietl 2002).

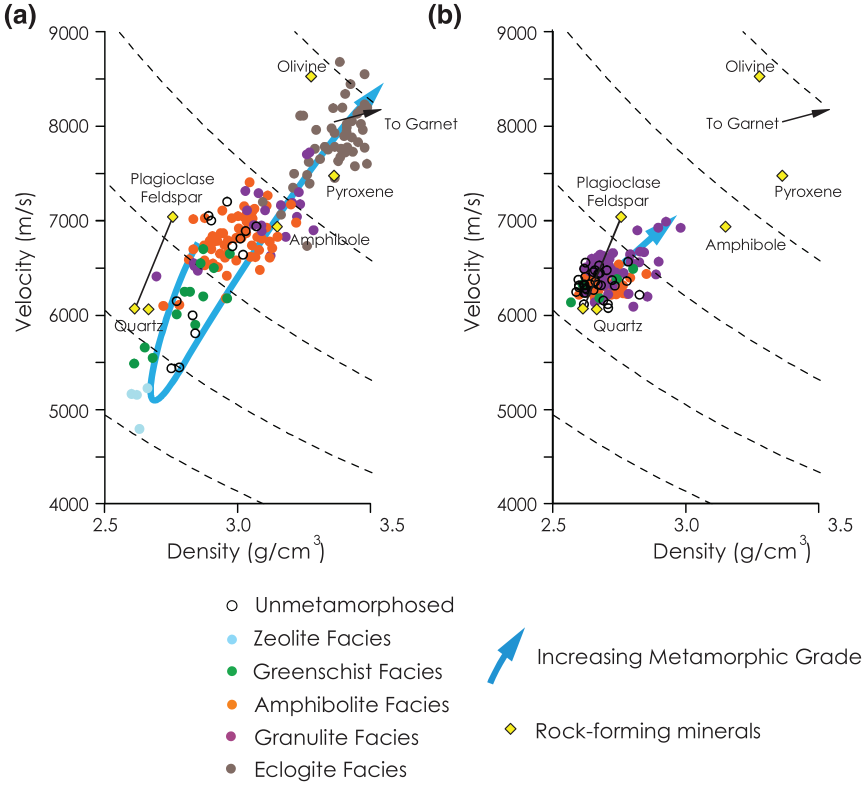
Figure 6 is an illustration of how seismic properties are affected by changes in metamorphic grade. Mafic and ultramafic rocks and fine-grained sedimentary rocks experience the greatest mineralogical changes with variations in metamorphic grade (which is why these rock types are mostly used to define metamorphic isograds, etc.). Importantly, mineralogical changes, and therefore changes in physical properties, in other rock types are often much more subtle. As has been well documented, mostly through studies of specimens from oceanic crust, significant changes in seismic properties occur with changing metamorphic grade in mafic rocks (see Christensen and Mooney 1995). Figure 6(a) shows how there is an initial decrease in velocity at the lower metamorphic grades, but then an increase in both velocity and density at the higher grades. In contrast, the effects of metamorphism on the seismic properties of felsic rocks are much smaller. Figure 6(b) shows data for unmetamorphosed felsic rocks (mostly described as granite), plus data for quartzo-feldspathic rocks metamorphosed at up to granulite facies. There is some evidence for an increase in density and velocity in rocks that have reached granulite facies, but this is modest compared to changes in the mafic rocks. This is simply because the mineralogy of quartzo-feldspathic rocks is much less affected by changes in metamorphic grade than mafic rocks, and in the latter case the new metamorphic minerals have significantly different seismic properties. An important implication of the data in Figure 6 is that because one kind of rock is affected more than the other, physical property contrasts between these two rock types will be different according to the metamorphic grade in the study area.

Figure 6 shows that the effects of metamorphism on physical properties of mafic rocks can be profound. This demonstrates that thinking, for example, in terms of the 'magnetic properties of basalt' and looking up values for 'basalt' in a textbook, is often meaningless. To allow a petrophysical measurement to be usefully interpreted, it is essential that metamorphic grade of the relevant rocks is noted. Ideally, the metamorphic history is known, because regressive metamorphism can reverse the effects of older high-grade events.

Alteration

Alteration in the context of this study involves modification of mineralogical content of a protolith through interaction

Figure 6 Effect of metamorphic grade on (a) mafic and (b) felsic rock. Velocity measurements are at a pressure of 400 MPa. Dashed lines are contours of equal acoustic impedance. There is little variation in the felsic rocks but significant variation in the mafic rocks. Data are from numerous published sources, including Fox, Schrieber and Peterson (1973) and Hurich *et al.* (2001). The dashed lines are contours of equal acoustic impedance.



with some fluid phase. The petrophysical consequences of alteration can be profound. The datasets that best demonstrate this were not collected for mineral exploration purposes. For example, there are very large (and readily available) petrophysical datasets collected as part of scientific initiatives whose primary purpose was to understand the nature of the oceanic crust, for example the Ocean Drilling Program. Dolomitization is another form of alteration that is well understood in a petrophysical context, for example Eberli *et al.* (2003), but only because it is a key control on the nature of some hydrocarbon reservoirs.

Petrophysically, a very important form of alteration is serpentinization, which is extremely common in mafic and ultramafic rocks and occurs in association with many mineral systems. Serpentinization involves the conversion of olivine and pyroxene to serpentinite-group minerals and magnetite. In so doing, it fundamentally changes rock physical properties. Velocity and density values are reduced by such a degree that rocks, which had some of the highest values in the geological environment in their unaltered state, are reduced to some of the lowest values when completely serpentinized (Fig. 7a). Magnetism is increased by orders of magnitude, for example Williams (2009), Dentith and Mudge (2014) and references therein.

Alteration associated with porphyry-style mineralization can also greatly affect physical properties, for example Hoschke (2011), Hope and Andersson (2016), Mitchinson, Enkin and Hart (2014). Byrne *et al.* (2019) demonstrate how it is possible to use susceptibility variation within an outcrop to track the degree of fracture-related alteration. Figure 7(b) shows changes in magnetic susceptibility and intensity of remanent magnetism associated with hydrothermal alteration at various porphyry copper deposits in Chile, plus data from unaltered rocks (Tapi *et al.* 2016). Zones of potassic alteration have magnetization as strong as the most magnetic country rocks, with chloritic alteration associated with slightly lower magnetization. However, destruction of magnetite under the geochemical conditions creating phyllic alteration results in both low susceptibility and low intensity of remanent magnetism.

Ideally, the alteration of a petrophysical sample should be quantified. Various geochemical alteration indices (AI) have long been in use to quantify the alteration in different mineral systems, notably volcanogenic massive sulphide systems, for example Large *et al.* (2001) and references therein. These indices provide a quantitative context in which to analyse the petrophysical data. Schetselaar *et al.* (2017) demonstrated that categorizing samples measured for seismic properties

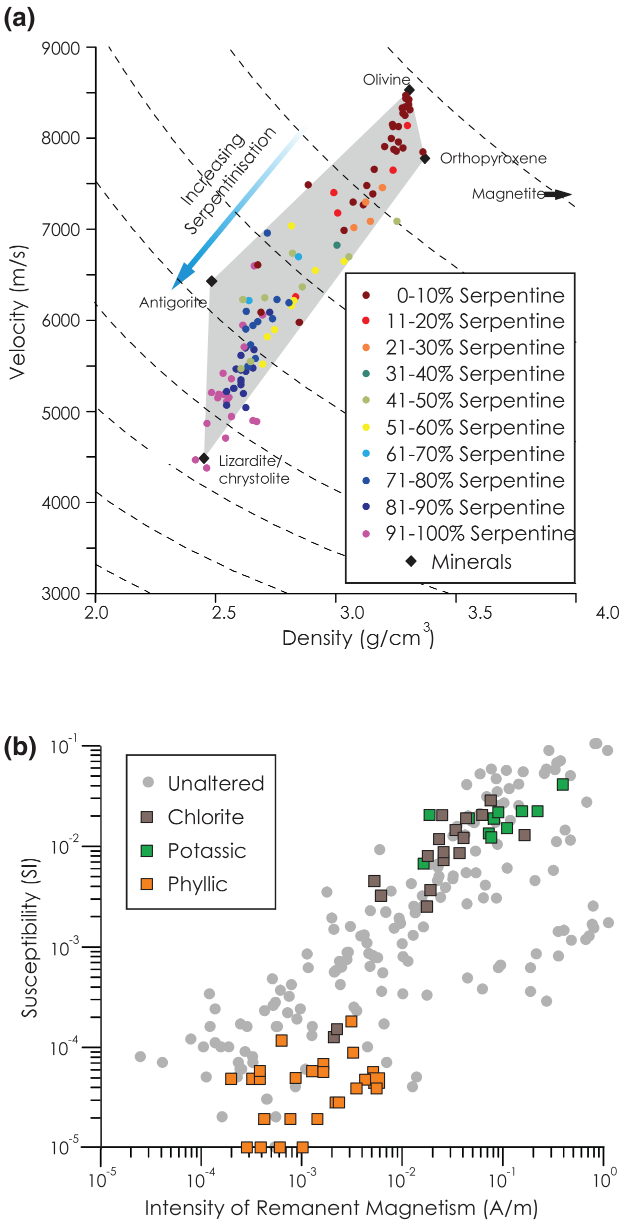


Figure 7 (a) Effect of serpentinization on the seismic properties of mafic and ultramafic rocks. The degree of serpentinisation is based on petrological analysis. Data are from various published sources. The dashed lines are contours of equal acoustic impedance. (b) Magnetic properties of rocks with different types of alteration from various porphyry copper deposits in Chile, and also unaltered country rocks, based on data and diagrams in Tapia *et al.* (2016).

using the AIs, in addition to seismic impedance between mafic and felsic protoliths, leads to an improved ability to understand seismic responses from the vicinity of a VMS deposit in Canada.

Figure 8 shows how alteration affects density and susceptibility data in the Great Bear magmatic zone in the Northwest Territories of Canada. This figure also incorporates a useful graphical method developed for the mapping of alteration zones. This involves the placing of a bar chart showing molar proportions of major metasomatic elements for each sample (Montreuil, Corriveau and Potter 2015). The Great Bear magmatic zone contains large iron-oxide alkali alteration systems noted for having high potential for iron oxide--apatite, iron oxide--copper--gold and affiliated ore deposits. Mineralogical and geochemical classification of the prograde iron oxide and alkali alteration facies reveals large variations in physical properties through the evolution of the metasomatic systems (Enkin, Corriveau and Hayward 2016). In particular, deep and early sodic alteration produced rocks having low densities and low magnetic susceptibilities. During calcium and iron precipitation, rocks became much more dense and of higher susceptibility, due to crystallization of amphibole and especially magnetite. Subsequent high temperature, potassic- and iron-altered rocks are characterized by co-crystallization of magnetite with K-feldspar or biotite, and as the transition from magnetite to hematite takes place, K-feldspar crystallizes instead of iron oxides leading ultimately to potassic felsites having low densities and susceptibilities. Subsequent cooler, shallower and more oxidized potassic--iron alteration produced high densities but moderate susceptibilities owing to crystallization of hematite.

Much work remains to be done to integrate different types of physical property data with quantitative alteration indices for different mineral systems, but this work is essential to understand geophysical responses in a mineral system context.

Location

In addition to geological data, it is essential that petrophysical data are associated with locations. This is automatically the case with downhole logs but outcrop measurements much less so. It goes without saying that the ‘average’ position of the outcrop will be recorded, but in some cases the relative positions of individual measurements are important.

When analysing petrophysical data at the scale of an exploration area, it is important to compare data grouped according to other categories, for example lithology, with respect to their location. This allows any variations between, say, granites in the study area to be recognized, which may in turn be indicative of variations in secondary post-intrusive processes such as alteration or in fact the presence of

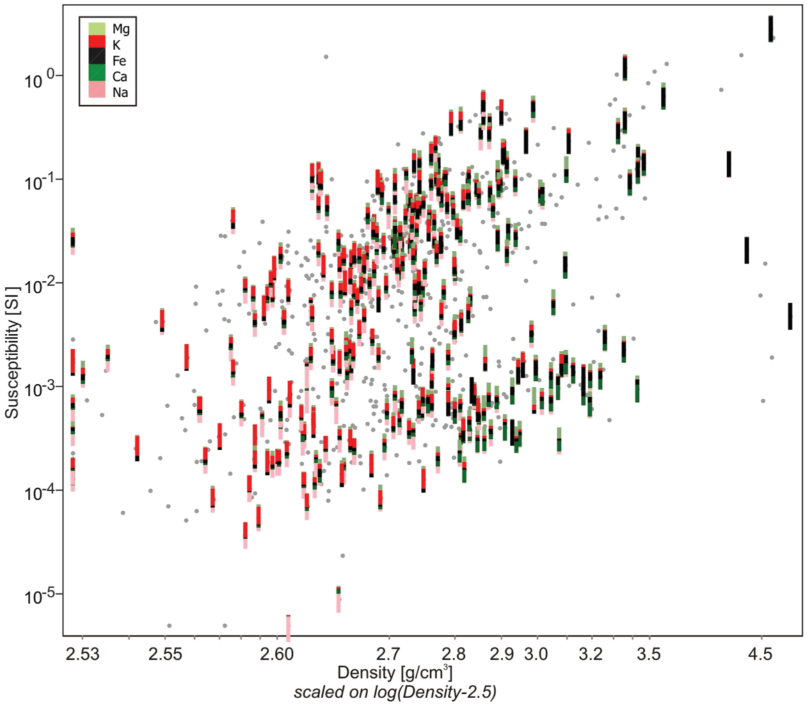


Figure 8 Plot of density and magnetic susceptibility of samples from Great Bear magmatic zone, using density scaled as log (density: 2.5 g/cm^3). Samples having geochemical analyses are represented by molar element alteration colour bars. Specifically, sodium in pink (chiefly representing albite), calcium in dark green (chiefly amphibole), iron in black (magnetite and/or specular hematite), potassium in red (chiefly K-feldspar) and magnesium in light green (chiefly chlorite). Compositions of these nearly completely metasomatized rocks have first-order influence on physical properties through resulting mineral assemblages and textures.

different granite suites, for example Aydin, Ferre and Aslan (2007), Sharma *et al.* (2011).

We illustrate aspects of petrophysical data display using a susceptibility dataset from the Archean Yilgarn Craton. Susceptibility measurements were made at 40 locations, with usually 50 and sometimes 25 individual measurements made at each locality. The 1:250,000 geology map of the area (Brakel et al. 1985) shows various types of granitoids, plus local occurrences of mafic granulites. In addition to the mafic granulites, there are six kinds of granitoid gneiss, differentiated according to their texture (banding) and mineralogy. The data used here are initially grouped according to the lithologies on this map.

Figure 9 shows susceptibility data from five locations. In all cases, the data come from the same lithological unit on the geological map of the area. The frequency histogram of the combined data is clearly multi-modal, with two lower susceptibility modes. When these individual sets of measurements are displayed as a function of location, it is immediately clear that there are two datasets with distinctly lower values occurring quite close together, although these two datasets are distinctly different. The geological reasons for this cannot be ascertained for certain because the necessary geochemical/mineralogical data, etc., were not collected. Ideally, a correlation between outcrop lithology and physical property should provide insight into the causative variation. But, in this instance, the lithology assigned to these data mentions both granite and adamellite, so the grouping of different lithologies within a single rock unit on a map (which is especially common for smaller scale geological maps) may be the reason for the multiple populations. Also possible are geographical differences in alteration, weathering, etc. Clearly recognizing this spatial control on the population is essential if the population's characteristics are to be fully understood.

At the scale of individual outcrops or drill core, analysis of the data relative to the positions of individual measurements may allow an observed frequency histogram to be better understood. This has already been shown in analysis of Figure 1. Figure 10(b) shows a skewed frequency histogram from a rock type which is explained by the fundamental 'zoned' nature of the rocks: in this case, the spinifex and cumulate zones of a komatiite flow. This fact is obvious when the data are presented in terms of the relative positions of the individual measurements (Fig. 10a).

Stratigraphy

Stratigraphic analysis of petrophysical data, that is by grouping data according to stratigraphic units, is especially important when geophysical datasets are being used to make

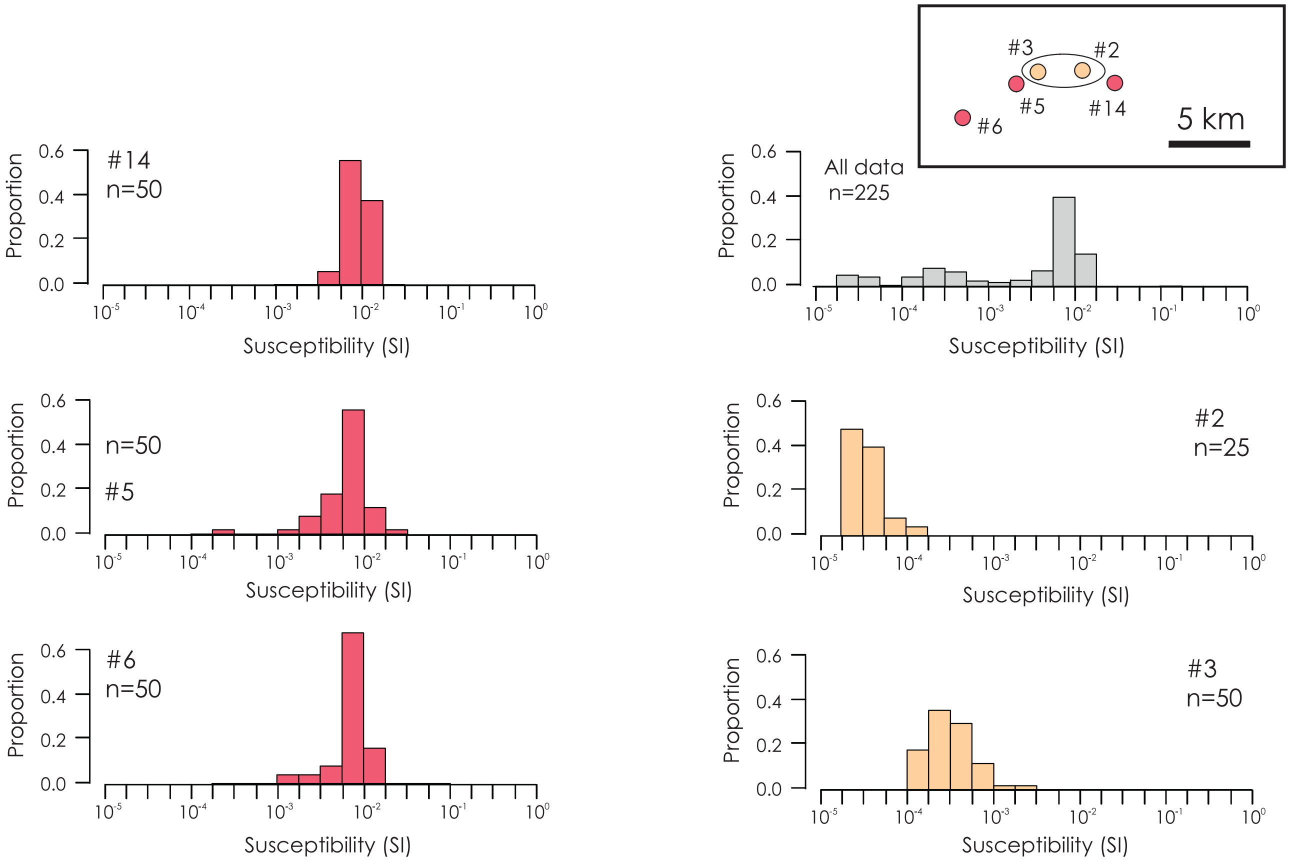


Figure 9 Frequency histograms of magnetic susceptibility from a granite--adamellite unit mapped near Dumbelyung area, Western Australia. The inset map shows the locations of each sampling site. The colours indicate the two different geophysical groups.

a pseudo-geological map. It is even more important when there is an existing geological (most likely lithological) map with which the geophysical interpretation must be integrated.

An analogy with field geological mapping is useful. When first in the field area, standard practice is to walk a series of traverses across geological strike to establish what constitutes a 'mappable unit'. It is important to remember that not every lithological boundary will be mapped. This is primarily a question of mapping scale. For example, an interbedded succession of sandstones and limestones, each bed being say a few metres thick, will be treated as a single mapping unit when the scale of mapping dictates that only units that are tens of metres thick can be shown on the map. Also important is the ease with which the rocks on either side of the contact can be discriminated. Key lithological differences, and the intervening contacts, which can be readily identified are important for producing an accurate map quickly and reliably. Ideally there is, somewhere in the local succession, some thin and distinctive unit that constitutes a 'marker' bed that can be readily mapped and in so doing defines the local geological structure.

Consider how petrophysical data might be analysed in the above context. The first objective is to display the data in stratigraphic order. This is achieved using the PPS (stacked probability plots) with the data grouped and displayed by stratigraphic unit. Data in this form can be used to easily identify the main petrophysical contrasts between stratigraphically juxtaposed units. These are the equivalents of 'key contacts.' Of course, because rocks can be geologically different but geophysically identical, say two sandstone units which are of different colour, so the petrophysical stratigraphy and the lithological stratigraphy do not necessary exactly correlate. On the other hand, the results of the other kinds of analysis described above may show that some of the rocks are geologically identical but geophysically different, say two basalts

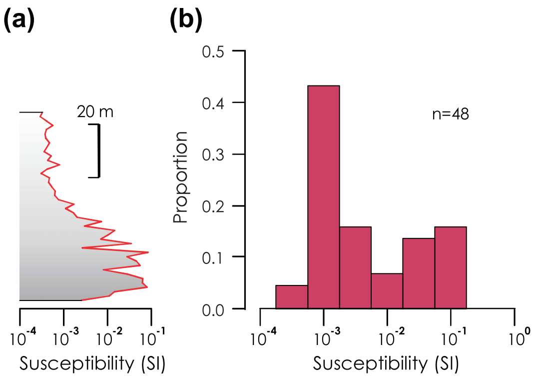


Figure 10 Magnetic susceptibility data from a komatiite flow near Coolgardie, Western Australia. (a) Log and (b) frequency histogram, based on data and diagrams in Keele (1994).

with different alteration. The PPS also allows ready identification of any marker units, which will have distinctly anomalous physical properties, but importantly this is anomalous relative to the adjacent stratigraphic units.

Figure 11 shows susceptibility data from three stratigraphic 'Members' of the Marra Mamba Iron Formation (MMIF), an economically important unit in the Hamersley Basin of northern Western Australia, plus the underlying Jeerinah Formation. Although four units are defined based on geological characteristics, the Jeerinah Formation (JF) and lowest Member of the MMIF, the Nammuldi Member (NaM), are geophysically indistinguishable. The Newman Member (NeM), the youngest unit, has a distinctly higher susceptibility whilst the underlying MacLeod Member (MM) is transitional between the NeM and NaM+JF. This means that a pseudo-geological map derived from magnetic data is probably not going to comprise the same stratigraphy as the geological map. A unit comprising the JF+NaM will show a transitional boundary with a unit comprising the MM+NeM. Importantly, if the stratigraphic order was different, such that the NM occurred between the MM and the NeM, then there are susceptibility contrasts at each of the stratigraphic contacts and the pseudo-geological map would be the same as the geological map.

Also shown in Figure 11 are data from some local iron ores. Put simply, the ores form by weathering and supergene enrichment of the iron formation, and most of the ore occurs in the NeM and to a lesser extent the MM. The loss of magnetism associated with the ore forming process (oxidation of magnetite to less magnetic hematite) is reflected in the frequency histogram. The overlap in the distributions for the ores and the NeM probably reflect the transitional nature of the process of converting iron formation to ore and some of the spread in the MM data may be due to partial conversion to ore. In this case, a combination of stratigraphic and lithological analysis of the data leads to an understanding of the main controls on susceptibility.

As with lithological-based analysis, the petrophysical data allow the geophysical responses of the various units to be predicted and compared with the geophysical response in areas where geological mapping suggests a given unit is present. A complex frequency histogram should be associated with variable geophysical response.

Porosity

It is important to recognize the fundamental control porosity, and to a lesser extent permeability, exert on all physical properties except magnetism. In some cases, observed physical property differences that are associated with changes in lithology, alteration, weathering, etc. may be due to associated changes in porosity–permeability. Figure 12 illustrates the fundamental control porosity plays on seismic velocity and density (see also Fig. 5). The data are a compilation, from the literature, of seismic properties of water-saturated dolostones and limestones. Both rock types define highly scattered linear trends from the properties of their constituent carbonate minerals towards the properties of water, that is the matrix minerals to the pore contents (Fig. 12a). Replotting the same data and classifying each point on the basis of porosity shows that changes of even a few percentage have a significant effect of the magnitude of velocity, and in particular, density (Fig. 12b).

Figure 12(c) shows a subset of the carbonate dataset where information is available about the nature of the pore space (Anselmetti and Eberli 1997; Eberli *et al.* 2003). The different types of porosity are demonstrated to be an influence on velocity. This is because of the way the different geometries of the pore space affect the stiffness of the rock. The samples with moldic and vuggy pores (framestones and boundstones) have the highest velocities. Interparticle/intercrystalline porosity produces velocities slightly below average whilst microporosity associated with carbonate mud rocks is associated with the lowest velocities for a given porosity. Densely cemented low-porosity specimens plot close to the values for the carbonate matrix minerals.

Figure 12 is a clear demonstration that it is very useful in relevant cases to record porosity–permeability during the acquisition of petrophysical data. However, this is incomplete information because of the influence of pore geometry.

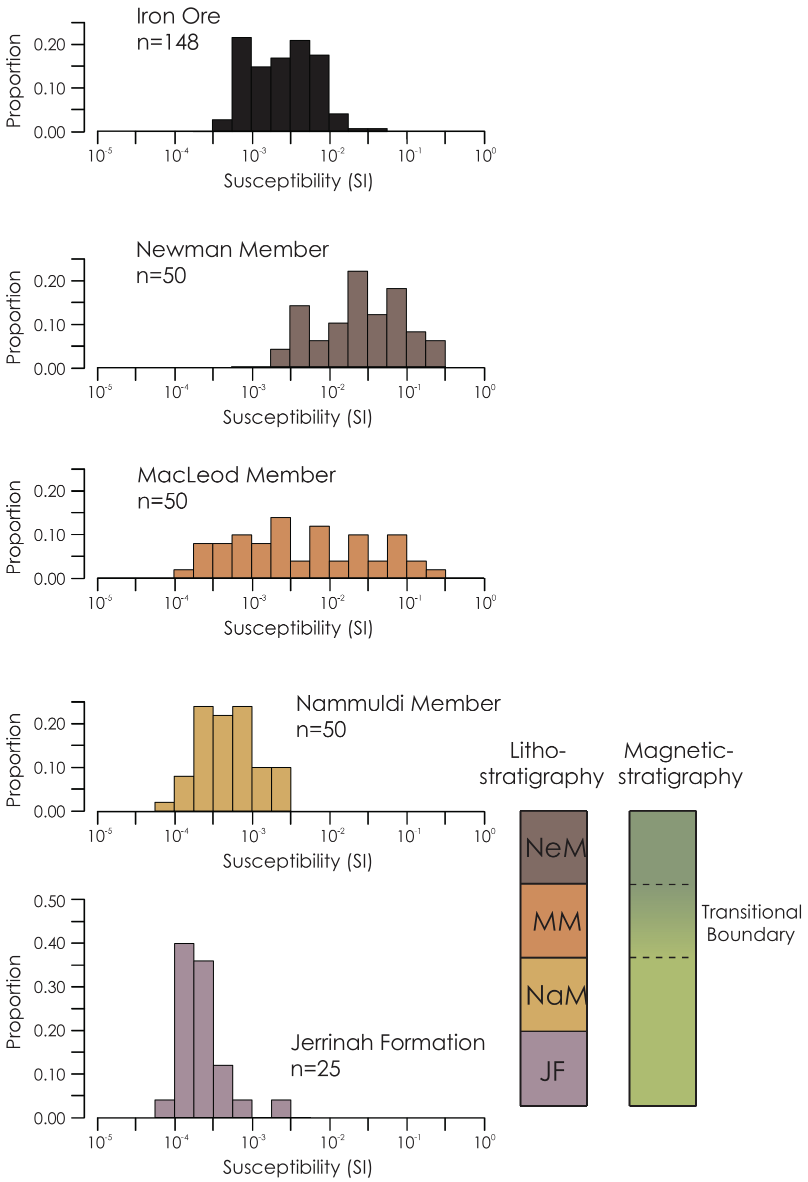


Figure 11 Frequency histograms of magnetic susceptibility from the Marra Mamba Iron Formation, Western Australia. The stratigraphy based on contrasts in susceptibility differs from that based on geological differences.

DISCUSSION

A conceptual framework for analysing petrophysical data in terms of geology and geological processes

The petrophysical properties routinely measured in mineral exploration (density, magnetic susceptibility, electrical properties and less commonly seismic velocity) have very different numerical/statistical population characteristics. Also, they are influenced by fundamentally different characteristics of the rocks. Below, we propose a new conceptual framework for relating hard rock physical properties to geological characteristics. We recognize three end-member types of behaviour which we call bulk, grain and texture control. It is convenient to use a ternary diagram to show how different types of physical property are influenced by these end-member characteristics (Fig. 13). Note that rock magnetic properties depend on a combination of paramagnetic and ferromagnetic minerals and these influences need to be considered separately.

Bulk control

Petrophysical properties associated with bulk control are those where the property of the rock can be estimated from

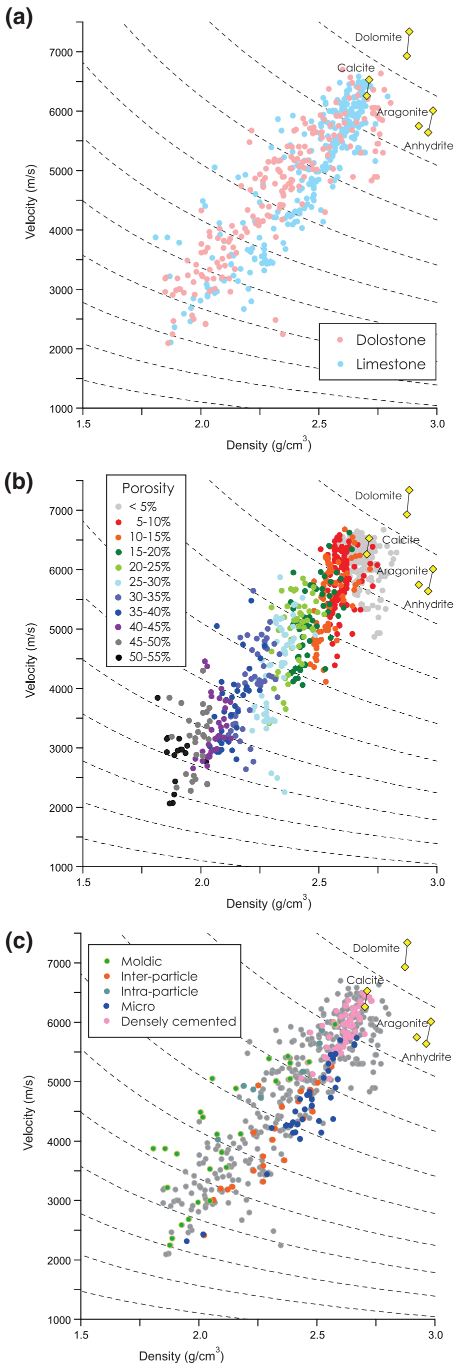


Figure 12 Seismic property data from carbonate rocks. Data are for saturated rocks at room temperature and pressures are from numerous published sources. (a) Data presented according to lithology. Note how the data form a continuous distribution from the seismic properties of their constituent minerals to the properties of the water that fills their pore space. (b) Data classified according to porosity and (c) data classified according to pore type (Anselmetti and Eberli 1997). Grey dots indicate that no information on pore structure is available and the dashed lines are contours of equal acoustic impedance.

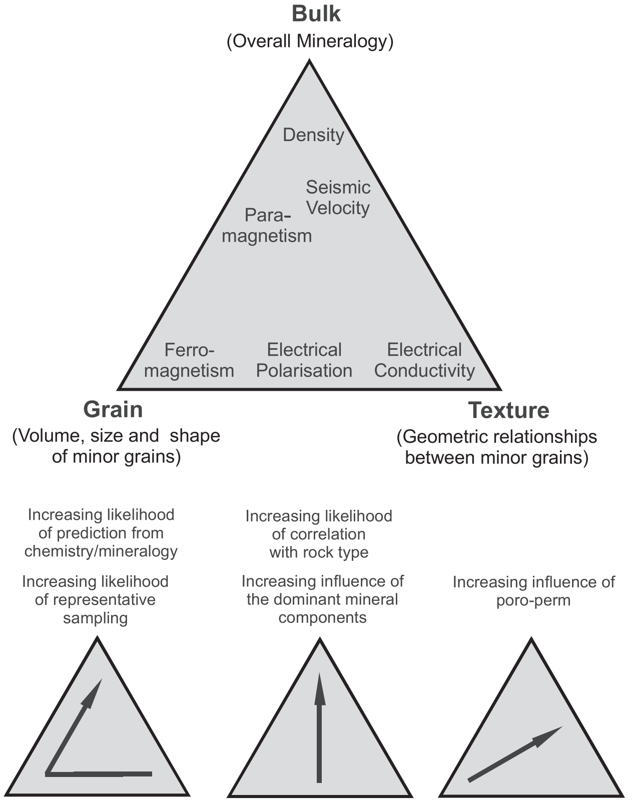


Figure 13 Conceptual framework describing the behaviour of various physical properties commonly measured by the mining industry.

some weighted volumetric ‘average’ of the properties of the mineral components. For example, the overall density of a rock is the average of the densities of the various component minerals (and pores) and is dominated by the most abundant mineral components. Because these minerals are those that are used as a basis for assigning a lithological name for the rock, it is expected that there will be a reasonable correlation between the petrophysical characteristics and the rock type, as demonstrated in Figure 3.

In principle, it is straightforward to calculate the rock’s physical properties from the mineral properties using some form of mixing model, (Williams and Dipple 2007; Williams and Chopping 2013), but in practice this is impossible to do very accurately. Reasons for this include:

- Individual mineral species vary in their chemistry and crystal structure, such that they have a range of properties also. The variation in properties, as a function of chemistry, is only documented for a very few species, however.
- A lithological name allows for a range of mineralogical composition, so the same rock type can have an associated range in physical properties. As noted previously, there is no

universally adopted mineralogy-based rock classification scheme and even when a particular scheme is adopted individuals interpret it in different ways.

A physical property that exhibits only bulk behaviour is density, hence it is plotted at the apex of the petrophysical ternary diagram (Fig. 13). Other physical properties exhibit bulk behaviour, but in combination with other kinds of behaviour. Paramagnetism shows bulk behaviour, but the (mainly) iron-bearing silicates do not usually comprise the entirety of the rock, and as such the requirement of the rock property being controlled by all the main mineral components is not met. Thus, paramagnetism is considered to show hybrid bulk-grain behaviour. Seismic velocity is often dominated by bulk property behaviour, but is plotted on the ternary diagram between bulk and texture characteristics due to the influence of the geometry, orientation and relative arrangement of the individual mineral grains or pore space which introduces a 'texture' influence on the measurement (Fig. 12c) (Bjarne and Almqvist 2017).

Because bulk behaviour depends on the majority of a rock's mineral components, representative sampling should be relatively straightforward because the property does not vary much with position. If the rock is heterogeneous at the sampling scale, for example centimetre to decimetre scale layering in gneisses and iron formations, then it is essential to adequately sample the associated variations (Byrne *et al.* 2019).

Grain control

Properties related to grain characteristics are those dominated by a minority component of the rocks and where, in addition to the amount of this component, behaviour is influenced by the size and shape of the mineral grains. Given the influence of a minor mineral component, a strong correlation with rock types is less likely because the relevant component will not be considered in assigning a lithological name. Ferromagnetism is a property that is influenced by grain-like characteristics. It is normally dominated by the presence of magnetite and although the volume present is a key control, the size, shape and geometrical distribution of the magnetite grains can have a significant effect on magnetic characteristics (Hargraves, Johnson and Chart 1991; Clark 1997). In rare very highly magnetic rocks, that is where ferromagnetic minerals comprise a significant proportion of the rocks, the relative positions of the grains may come in to play also, due to inter-grain magnetic interactions and this leads to a texture control (Austin *et al.* 2014).

The theoretical calculation of magnetic properties from geochemistry is extremely challenging. The requirement for iron for magnetic minerals (ignoring the influence of nickel- and manganese-bearing species) suggests a correlation with magnetism, but whether that iron is in paramagnetic silicates or oxides, or ferromagnetic oxides, is a complex function of the chemical and physical conditions under which the minerals are created (Grant 1984a,b; Rauen Soffel and Winter 2000; Clark 2014; Dentith and Mudge 2014). However, empirical data on magnetic properties and the volume of magnetic grains in a rock sample are readily available (Clark 2014). Information on grain size and shape would require some kind of image of a sample/core surface, or even microscopic examination for very fine grained minerals. For downhole data, televiewer imagery might be able to provide coarse scale grain crystal imagery, albeit on a small volume of rock.

Because grain behaviour is controlled by a minority mineralogical component, care with sampling is required. It may not be obvious if a minor mineral component is uniformly distributed in the rock and, as demonstrated in Figure 1, magnetic properties can be highly heterogeneous in some rock types.

Texture control

Like grain behaviour, texture is also controlled by a minority component(s) of the rock. The physical property most dominated by texture behaviour is electrical conductivity. Importantly, the conductive minerals in the rock can form a continuous conductive networks like wires, or chargeable unconnected nuggets like capacitors. Whether this occurs depends on the rock fabric, that is texture, in layered rock types this is favoured. To some extent, it is also influenced by the shape of the individual conductive grains and so there is a component of grain behaviour.

Quantifying texture-controlled behaviour as exhibited by electrical conductivity, either by measurements on samples, or forward modelling based on empirical or theoretical considerations, is fraught with difficulty. Studies have demonstrated that current flow through even some centimetre scale samples is highly heterogeneous, for example Roach and Fitzpatrick (2001), introducing a perhaps intractable problem in scalability between the petrophysical measurement and the volume of material 'sampled' by electrical and electromagnetic geophysical methods.

Further complicating the problem is the great influence of porosity and pore contents on electrical measurements. Not only is pore volume and content important, but also pore geometry. This has been long recognized in the petroleum industry where it is common practice to define a 'formation factor' that relates the bulk resistivity of the rock to that of the pore contents. This is a measure of the 'texture' of the pore space.

Still further complicating the issue is whether inductive or galvanic measurements are more appropriate, the ability to reproduce the natural formation fluids and pressure conditions in the laboratory (and hence pore space) and the creation of crack porosity during drilling. Generally, *in situ* measurements are preferable.

We note the near equivalence of measuring electrical characteristics and understanding the extremely variable and heterogeneous porosity–permeability characteristics of carbonate reservoirs and speculate that ideas developed by the petroleum industry for quantifying reservoir properties may be relevant to understanding electrical properties as required for mineral exploration.

Discussion of the BGT petrophysical model

The bulk, grain and texture (BGT) petrophysical model provides a simple conceptual framework to predict how a geological process will affect rock physical properties. It therefore provides a context in which to understand geophysical responses in terms of geological processes when there is limited geological control. For example, deformation affects grain shape and rock texture and hence will alter magnetic and electrical properties. Regional metamorphism changes mineralogy, grain size and shape, and so potentially affects all physical properties. The BGT model also provides for an appreciation of the importance of porosity. With respect to bulk behaviour, the contents of the pore space simply act like any other 'mineralogical' component of the rock. The range of density of common minerals is rather small, between about 2.5 and 3.5 g/cm^3. However, the gaseous and liquid contents of pore contents have much lower density than any mineral, so even a small amount of pore space has a disproportionate influence on the 'average' (bulk) density. Porosity affects electrical properties by providing flow paths for ionic conduction and allowing disseminated conductive grains to be in contact with conductive pore fluids. Thus, it exhibits texture control as well as bulk control. Geological processes that affect pore volume affect all the petrophysical properties, but if only grain geometry is changed, then it is texture behaviour that is most affected. Thus, the influence of porosity decreases towards the grain apex of the ternary diagram (Fig. 13).

The BGT petrophysical model provides a simple explanation for understanding whether different physical properties are expected to correlate with each other. Put simply, the closer the individual petrophysical properties plot on the BGT ternary diagram, the more likely they are to correlate. Further, the closer each physical property plots to the bulk apex on the BGT diagram, the more reliable is the last sentence. This is because of the greater variability in the texture and grain-controlled properties.

Numerical analysis of petrophysical data

There is on-going research on ways to numerically analyse petrophysical data, and in particular how to automatically find patterns within, and between, different kinds of data, for example Berube *et al.* (2018). This work is beyond the scope of this paper, but the results are relevant to this work. There are undoubtedly multiple sources of variation in a given petrophysical dataset, with a population of observations very likely comprising a series of overlapping sub-populations. In addition to the geological factors described here, another possible source of sub-populations is combining measurements made using different instruments with different acquisition practices. Deconvolving the data and recognizing the constituent 'sub-populations' is not a simple problem. Further, when comparing different types of data in cross-plots, different 'sub-populations' of one type of data have particular relationships with different 'sub-populations' of other types of data. The potential for extreme complexity is obvious. The geological context for petrophysical variations previously described above provides a context to understand relationships identified purely from numerical algorithms applied to petrophysical data.

The ideal petrophysical database?

Various government agencies around the world have created petrophysical databases, for example Ruotoistenmäki and Birungi (2015), Enkin (2014) and Enkin et al. (2018). The most common physical properties in these databases are density and magnetic susceptibility but other properties may be present. Other information, in addition to the physical properties, is usually related to how the measurement was made, location, stratigraphic unit and lithology.

As has been demonstrated above, weathering, alteration, metamorphism and porosity are key controls on the physical properties in the hard rock environment. This information should be provided too, and would be even more useful if geochemical and mineralogical information was also provided so the user could quantify how these variables affect the measurements. With the general availability of portable instruments for geochemical analysis, this information can be readily provided, although a key limitation is the poor sensitivity of these portable instruments for elements with low atomic numbers. Similarly, information on key alteration minerals such as chlorite and serpentine group possibly accessible through hyperspectral imagery would be most useful. In general, and especially for physical properties exhibiting texture and grain behaviour, it is useful to have information about the abundance and grain characteristics of the common 'geophysical' minerals: these being metal oxides, sulphides and graphite. Also important is information about the rock's texture. Ideally, this could be derived from digital imagery of the rock, either of the relevant sample or in the case of downhole measurements, from a televiewer.

An ideal database should contain both downhole logging and sample measurements. The logs have the advantage of *in situ* measurements and large data volumes. Samples have the advantage of better lithological determination.

Petroleum industry petrophysics relies heavily on combining different kinds of measurement. The mining sector tends to measure far fewer properties, often only a single property (most commonly that is magnetic susceptibility). There is an urgent need for comprehensive multiple parameter databases of physical properties from various kinds of mineralized environment. This will allow strategies to be developed for multi-parameter interpretations based on empirical relations between different parameters, which will very likely help us better understand how geological processes affect physical properties. These data will also be useful for framing modelling strategies based on simultaneous inversion of different types of geophysical data. One of us (JM) is currently working on this problem.

CONCLUSION

Petrophysical properties vary in a complex fashion and their relationship with geological processes is similarly complex. Making representative measurements is difficult and time consuming. Nevertheless, it is hard to make a case for successful exploration for targets at depth without interested groups in industry, academia and government accepting the associated challenges.

It was argued here that the mining industry would benefit from analysing petrophysical data in a more rigorous geological framework. A given dataset needs to be treated as an overall population that is composed of a series of overlapping sub-populations. Identifying these sub-populations requires collection of all stratigraphical, locational, geochemical and mineralogical data along with the physical property measurement(s). This enables controls on petrophysical properties other than lithology to be recognized, and in many cases these variables have more influence than lithology. Although the workflow described above requires a considerably greater investment of time and resources than in current practice, understanding the geological causes of variations in physical properties leads to a better understanding of geophysical responses in the absence of detailed geological control, as will be the case as exploration targets are sought at greater depth and under cover.

To fully realize the potential usefulness of petrophysical and geophysical datasets in this context requires that the quite limited datasets used to present our arguments are expanded to a comprehensive database covering as many kinds of physical properties and mineralized environments as is possible. There are a number of studies that integrate geochemistry and/or mineralogy and physical properties, for example Aydin *et al.* (2007), Sharma *et al.* (2011), van der Wielen *et al.* (2013), Wendt *et al.* (2013), Li, Zuo and Yang (2014). These show that the relationships are often complex, especially for properties which do not display 'bulk' behaviour. These studies are confined to specific areas and are usually working on problems of academic interest and often only a single physical property. There is a need for systematic studies of all relevant physical properties from the different mineral systems if geophysical data are to be used to their maximum potential as sources of geological information about mineral system components in the sub-surface. Studies such as Berube *et al.* (2018), Clark (2014), Sandrin *et al.* (2009), Williams (2009) and Aguilef, Araya Vargas and Yanez (2017) have begun this task, but much work remains to be done.

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ORCID

Michael Dentith https://orcid.org/0000-0001-5284-430X
William Morris https://orcid.org/0000-0002-3174-8121
Cameron Adams https://orcid.org/0000-0002-9926-0640
Barry Bourne https://orcid.org/0000-0002-9782-7316

REFERENCES

Aguilef S., Araya Vargas J. and Yanez G. 2017. Relationship between bulk mineralogy and induced polarisation responses in iron oxide-copper-gold and porphyry copper mineralisation, northern Chile. *Exploration Geophysics* **48**, 353–362.

Anselmetti F.S. and Eberli G.P. 1997. Sonic velocity in carbonate sediments and rocks. In: *Carbonate Seismology* (eds I. Palaz and K.J. Marfurt), pp. 53–74. Tulsa, OK: Society of Exploration Geophysicists.

Austin J., Geuna S., Clark D. and Hillan D. 2014. Remanence, self-demagnetization and their ramifications for magnetic modelling of iron oxide copper-gold deposits: an example from Candeleria, Chile. *Journal of Applied Geophysics* **109**, 242–255.

Aydin A., Ferre E.C. and Aslan Z. 2007. The magnetic susceptibility of granitic rocks as a proxy for geochemical composition - example from the Saruhan Granitoids, Turkey. *Tectonophysics* **441**, 85–95.

Berube C.L., Olivo G.R., Chouteau M., Perrouty S., Shamsipour P., Enkin R.J., *et al.* 2018. Predicting rock type and detecting hydrothermal alteration using machine learning and petrophysical properties of the Canadian Malartic ore and host rocks, Pontiac Subprovince, Quebec, Canada. *Ore Geology Reviews* **96**, 130–145.

Bjarne S.G. and Almqvist D.M. 2017. Seismic properties and anisotropy of the continental crust: predictions based on mineral texture and rock microstructure. *Reviews of Geophysics* **55**, 367–433.

Bourne B.T., Dentith M.C., Trench A. and Ridley J. 1993. Physical property variations within Archaean granite-greenstone terrane off the Yilgarn Craton, Western Australia: the influence of metamorphic grade. *Exploration Geophysics* **24**, 367–374.

Brakel A.T., Moncrieff J.S., Muhling P.C. and Chin R.J. 1985. Dumbelyung Sheet SI 50–7. Geological Survey of Western Australia.

Byrne K., Lesage G., Morris W.A., Enkin R.J., Gleeson S.A. and Lee R.G. 2019. Variability of outcrop magnetic susceptibility and its relationship to the porphyry Cu centers in the highland valley copper district. *Ore Geology Reviews* **107**, 201–217.

Christensen N.I. and Mooney W.D. 1995. Seismic velocity structure and composition of the continental crust: a global view. *Journal of Geophysical Research* **100**, 9761–9788.

Clark D.A. 1997. Magnetic petrophysics and magnetic petrology: aids to geological interpretation of magnetic surveys. *AGSO Journal of Australian Geology and Geophysics* **17**, 83–103.

Clark D.A. 2014. Magnetic effects of hydrothermal alteration in porphyry copper and iron-oxide copper-gold systems: a review. *Tectonophysics* **624–625**, 46–65.

Delius H., Brewer T.S. and Harvey P.K. 2003. Evidence for textural and alteration changes in basaltic lava flows using variations in rock magnetic properties (ODP Leg 183). *Tectonophysics* **371**, 111–140.

Dentith M. and Mudge S.T. 2014. *Geophysics for the Mineral Exploration Geoscientist*. Cambridge University Press.

Duzgoren-Aydin N.S., Aydin A. and Malpas J. 2002. Re-assessment of chemical weathering indices: case study on pyroclastic rocks of Hong Kong. *Engineering Geology* **63**, 99–119.

Eberli G.P., Baechle G.T., Flavio S. and Anselmetti F.S. 2003. Factors controlling elastic properties in carbonate sediments and rocks. *The Leading Edge* **22**, 654–660.

Emerson D.W. and Macnae J. 2001. Further physical property data from the Archaean regolith, Western Australia. *Preview* **92**, 33–37.

Enkin R. 2014. The rock physical property database of British Columbia, and the distinct petrophysical signature of the chilcotin basalts. *Canadian Journal of Earth Sciences* **51**, 327–338.

Enkin R.J., Corriveau L. and Hayward N. 2016. Metasomatic alteration control of petrophysical properties in the great bear magmatic zone (Northwest Territories, Canada). *Economic Geology* **111**, 2073-2085.

Enkin, R.J. 2018 "The Canadian Rock Physical Property Database: first public release", *GSC Open File* **8460**, 60p.

Fox P.J., Schrieber E. and Peterson J.J. 1973. The geology of the oceanic crust: compressional wave velocities of oceanic rocks. *Journal of Geophysical Research* **78**, 5155–5172.

Grant F.S. 1984a. Aeromagnetics, geology and ore environments, I. Magnetite in igneous, sedimentary and metamorphic rocks: an overview. *Geoexploration* **23**, 303–333.

Grant F.S. 1984b. Aeromagnetics, geology and ore environments, I. Magnetite and ore environments. *Geoexploration* **23**, 335–362.

GSL 1995. The description and classification of weathered rocks for engineering purposes. Geological society engineering group working party report. *Quarterly Journal of engineering Geology* **28**, 207–242.

Hargraves R.B., Johnson D. and Chart C.Y. 1991. Distribution anisotropy: the cause of AMS in igneous rocks? *Geophysical Research Letters* **18**, 2193–2196.

Henkel H. and Guzman M. 1977. Magnetic features of fracture zones. *Geoexploration* **15**, 173–181.

Hope M. and Andersson S. 2016. The discovery and geophysical response of the Atlántida Cu–Au porphyry deposit, Chile. *Exploration Geophysics* **47**, 237–247.

Hoschke T. 2011. *Geophysical Signatures of Copper-Gold Porphyry and Epithermal Gold Deposits, and Implications for Exploration*. Hobart, Australia: University of Tasmania.

Hurich C.A., Deemer S.J., Indares A. and Salisbury M. 2001. Compositional and metamorphic controls on velocity and reflectivity in the continental crust: an example from the Grenville Province of Eastern Quebec. *Journal of Geophysical Research* **B106**, 665–682.

Irving E., Molyneux L. and Runcorn S.K. 1966. The analysis of remanent intensities and susceptibilities of rocks. *Geophysical Journal of the Royal Astronomical Society* **10**, 451–464.

Keele R.A. 1994. Magnetic susceptibilities of rocks associated with some Archean gold deposits in Western Australia. In: *Geophysical Signatures of Western Australian Mineral Deposits* (eds M.C. Dentith, K.F. Francombe, S.E. Ho, J.M. Shepherd, D.I. Groves and A. Trench), pp. 315–330. Crows Nest, Australia, Australian Society of Exploration Geophysicist.

Kontny A. and Dietl C. 2002. Relationships between contact metamorphism and magnetite formation and destruction in a pluton's aureole, White-Inyo Range, Eastern California. *Geological Society of America Bulletin* **114**, 1438–1451.

Lapointe P., Morris W.A. and Harding K.L. 1986. Interpretation of magnetic susceptibility: a new approach to geophysical evaluation of the degree of rock alteration. *Canadian Journal of Earth Sciences* **23**, 393–401.

Large R.J., Gemmell B., Paulick H. and Houston D.L. 2001. The alteration box plot: a simple approach to understanding the relationship between alteration mineralogy and lithogeochemistry associated with volcanic-hosted massive sulphide deposits. *Economic Geology* **96**, 957–971.

Larsson L.O. 1977. *Statistical Treatments of in-situ Measurements of Magnetic Susceptibility*. Sveriges Geologiska Undersokning, Serie C727.

Latham A.G., Harding K.L., Lapointe L., Morris W.A. and Balch S.J. 1989. On the lognormal distribution of oxides in igneous rocks, using magnetic susceptibility as a proxy for oxide mineral concentration. *Geophysical Journal International* **96**, 179–184.

Li Y., Zuo R. and Yang M. 2014. The relationships between magnetic susceptibility and elemental variations for mineralized rocks. *Journal of Geochemical Exploration* **146**, 17–26.

McCuaig T.C. and Hronsky J.M.A. 2014. The mineral system concept: the key to exploration targeting. *Society of Economic Geologists Special Publication* **18**, 153–175.

Mitchinson D., Enkin R.J. and Hart C.J.R. 2014. Linking porphyry deposit geology to geophysics via physical properties: adding value to geoscience BC geophysical data. Geoscience BC Report 2013–14.

Montreuil J.-F., Corriveau L. and Potter E.G. 2015. Formation of albitite hosted uranium within IOCG systems: the Southern Breccia, great bear magmatic zone, Northwest Territories, Canada. *Mineralium Deposita* **50**, 293–325.

Mwenifumbo C.J., Elliot B.E., Jefferson C.W., Bernius G.R. and Pflug K.A. 2004. Physical rock properties from the Athabasca group: designing geophysical exploration models for unconformity uranium deposits. *Journal of Applied Geophysics* **55**, 117–135.

Olesen O., Henkel H., Kaada K. and Tveten E. 1991. Petrophysical properties of a prograde amphibolite – granulite facies transition zone at Sigerfjord, Vesteralen, Northern Norway. *Tectonophysics* **192**, 33–39.

Ontario Geological Survey 2001. Physical rock property data from the Matheson and Kirkland Lake areas. Ontario Geological Survey Miscellaneous Release Data – 91.

Pola A., Crosta G., Fusi N., Barberini V. and Norini G. 2012. Influence of alteration on physical properties of volcanic rocks. *Tectonophysics* **566–567**, 67–86.

Rauen A., Soffel H.C. and Winter H. 2000. Statistical analysis and origin of the magnetic susceptibility of drill cuttings from the 9.1-km-deep KTB drill hole. *Geophysical Journal International* **142**, 83–94.

Roach M. and Fitzpatrick A. 2001. Continuity and current mapping – New laboratory techniques for study of the electrical properties of sulphide rocks. SEG international Exposition and Annual meeting, San Antonio, TX, Extended Abstracts.

Ross P.S., Bourke A. and Fresia B. 2013. A multi-sensor logger for rock cores: methodology and preliminary results from the matagami mining camp, Canada. *Ore Geology Reviews* **53**, 93–111.

Ruotoistenmäki T. and Birungi N.R. 2015. Petrophysical database of Uganda. *Journal of African Earth Sciences* **106**, 17–39.

Sandrin A., Edfelt A., Waight T.E., Berggren R. and Elming S.-A. 2009. Physical properties and petrologic description of rock samples from an IOCG mineralized area in the northern fennoscandian shield, Sweden. *Journal of Geochemical Exploration* **103**, 80–96.

Schetselaar E., Bellefleur G., Craven J., Roots E., Cheraghi S., Shamsipour P. *et al.* 2017. *Geologically Driven 3D Modelling of Physical Rock Properties in Support of Interpreting the Seismic Response of the Lalor Volcanogenic Massive Sulphide Deposit, Snow Lake, Manitoba, Canada*. London, UK, Geological Society.

Schwarz E. 1991. Magnetic expressions of intrusions including magnetic aureoles. *Tectonophysics* **192**, 191–200.

Sharma R., Gupta V., Arora B.R. and Sen K. 2011. Petrophysical properties of the Himalayan granitoids: implication on composition and source. *Tectonophysics* **497**, 23–93.

Tapia J., Townley B., Cordova L., Poblete F. and Arriagada C. 2016. Hydrothermal alteration and its effects on the magnetic properties of Los Pelambres, a large multistage porphyry copper deposit. *Journal of Applied Geophysics* **132**, 125–136.

Van der Wielen S.E., Fabris A.J., Halley S.W., Keeling J.L., Gordon G.A., Keeping T. *et al.* 2013. An exploration strategy for IOCG mineral systems under deep cover. *MESA Journal* **71**, 18–30.

Wendt A.S., Vaughan A.P.M., Ferraccioli F. and Grunov A.M. 2013. Magnetic susceptibilities of rocks of the Antarctic Peninsula: implications for the redox state of the batholith and extent of metamorphic zones. *Tectonophysics* **585**, 48–67.

Williams N.C. 2009. Mass and magnetic properties of 3D geological and geophysical modelling of the southern Agnew-Wiluna greenstone belt and leinster nickel deposits, Western Australia. *Australian Journal of Earth Sciences* **56**, 1111–1142.

Williams N.C. and Chopping R. 2013.*Using MineralMapper3D to Map Alteration from Hand Specimens, Downhole Data and UBC-GIF GRAV3D/ MAG3D Inversions (Accompanies MineralMapper3D Software)*. Canberra, Australia, Geoscience Australia.

Williams N.C. and Dipple G. 2007. Mapping subsurface alteration using gravity and magnetic inversion models. *Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration*, pp. 461–472.

Wyborn L.A.I., Heinrich C.A. and Jaques A.L. 1994. Australian Proterozoic mineral systems: essential ingredients and mappable criteria. *Proceedings of the Australian Institute of Mining and Metallurgy Annual Conference, Melbourne, Australia*.